REPORT DOCUMENTATION PAGE	*Form Approved OMB No. 0704-0188*

1. REPORT DATE *(DD-MM-YYYY)*	**2. REPORT TYPE**	**3. DATES COVERED** *(From - To)*
10-09-2008	Final Report	01/07/2004 - 30/06/2008

4. TITLE AND SUBTITLE
Cross-Scale Coupling: Modeling Oceanic Variability from the Pacific Basin Scale to Local Coastal Domains Along the North America West Coast (NAWC)

5a. CONTRACT NUMBER

5b. GRANT NUMBER
N00014-04-1-0401

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
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5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
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8. PERFORMING ORGANIZATION REPORT NUMBER
MC-23060

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Office of Naval Research
875 North Randolph Street
Arlington, VA 22203-1995

10. SPONSOR/MONITOR'S ACRONYM(S)
ONR

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT
We investigate the space-time structure and causal mechanisms for cross-scale coupling (i.e., from simulations of global and basin-scale circulations and local flows) as it occurs in the oceanic circulation & water properties along the North American West Coast (NAWC) within the context of large-scale changes throughout the Pacific basin. The cross-scale coupling is manifested over a broad range of time scales, ranging from synoptic and intra-seasonal (with cross-scale communication by barotropic Rossby and coastal waves) to decadal or longer (with slowly varying quasi-equilibrium currents over the whole basin). Simulations are for both the Pacific as a whole and for the NAWC reational and local coastal (littoral) subdomains, using either eddy-excluding or eddy-permitting grid resolutions for the former and fine mesoscale resolutions for the latter.

15. SUBJECT TERMS
cross-scale coupling ocean models, interannual variability, El Nino

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			James C. McWilliams
U	U	U	UU		**19b. TELEPHONE NUMBER** *(Include area code)* 310-206-2829

Cross-Scale Coupling: Modeling Oceanic Variability from the Pacific Basin Scale to Local Coastal Domains Along the North America West Coast (NAWC)

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Award #: N00014-04-1-0401

LONG-TERM GOALS

Realistic, skillful numerical simulations of oceanic physical-ecological-biogeochemical processes are urgently needed to address many societal problems (*e.g.,* naval operations, climate change, coastal eutrophication, fisheries). An important requirement, as yet rarely met, is the capability of simulating both the global or basin-scale circulation and the more local flows that respond to the larger scale changes ("down-scaling"), and sometimes feedback on them and influence their evolution ("up-scaling"). We have proposed to investigate the space-time structure and causal mechanisms for this cross-scale coupling as it occurs in the oceanic circulation and water properties along the North American West Coast (NAWC) within the context of large-scale changes throughout the Pacific basin. The cross-scale coupling is manifested over a broad range of time scales, ranging from synoptic and intra-seasonal (with cross-scale communication by barotropic Rossby and coastal waves) through seasonal and interannual (with transient currents, mesoscale eddies, and baroclinic waves) to decadal or longer (with slowly varying quasi-equilibrium currents over the whole basin). Simulations will be made both for the Pacific as a whole and for the NAWC regional and local coastal (*a.k.a.* littoral) subdomains, using either eddy-excluding or eddy-permitting grid resolutions for the former and fine mesoscale resolutions for the latter.

OBJECTIVES

Historically, our research on regional oceanic dynamics has mostly dealt with the U.S. West Coast (USWC) between the Mexican and Canadian borders. Taking advantage of this experience, we are currently focusing on the impact of the 1997-1998 El Niño on the ocean dynamics (mean currents and mesoscale variability) and thermohaline structure off California and Oregon. This also has the advantage of providing us with a large *in situ* dataset well suited for model validations. We have made signifcant advance in the modeling of NAWC and the study of oceanic processes in this region. The major results from this project is sumarized here, along with discussions on outstanding issues and ongoing efforts to fix them.

APPROACH

We are seeking an integrated, coast-wide view of the Pacific + NAWC physical variability. Our general approach is to determine the degree of relevance of four hypotheses and potentially refine them; each corresponds to a specific time/space scale window.

1- Intraseasonal Forcing Effects on the NAWC: we will consider how sequences of synoptic and longer intraseasonal atmospheric events (*e.g.,* storms and their associated coastally trapped wave signals, river run-off, and sea breeze) lead to changes in the NAWC mean state through rectification (*i.e.,* time-averaged fluxes). Our hypothesis, to be tested, is that there is no significant upscaling in either space or time (*i.e.,* none of these phenomena—including coastal waves generated by storms—induces important rectification in the quasi-equilibrium circulation).

2- Local Seasonal Forcing Effects on the NAWC: fluctuations of the quasi-equilibrium on the seasonal scale are primarily induced by local wind variability, with remote influences and buoyancy forcing secondary. In the Marchesiello et al., 2003 simulation of mean-seasonal equilibrium CCS, this interpretation seems valid. Our hypothesis is that the mesoscale-eddy modulation in response to the local seasonal forcing occurs for the entire NAWC region.

3- Remote Interannual Downscaling Effects on the NAWC: on interannual time scales, the quasi-equilibrium of the Mexican, U.S., and Canadian coastal sectors is strongly influenced by the coherent poleward propagation of wave-like anomalies in sea level, pycnocline slope, and circulation. These anomalies are generated, or at least pass through, the tropical region in the up-wave direction from the NAWC (*e.g.,* ENSO variations). Response to local forcing and advective dynamics (especially mesoscale) may modulate wave-instigated fluctuations.

4- Decadal Downscaling Effects on the NAWC: on decadal time scales, the North Pacific variability mainly occurs as a basin-wide atmospheric pattern change, most famously identified as the PDO. Its anomalous forcing induces quasi-stationary, basin-wide changes in SST, pycnocline depth and circulation. Therefore we hypothesize the NAWC decadal variability arises as a quasi-equilibrium response to the combined influence of remote and local surface forcing anomalies.

Practically, our approach involves coupling a low resolution (50 and 25km as of yet) Pacific solution of Regional Ocean Modeling System (ROMS) together with regional configurations (at high horizontal resolution, typically 5km) focused on NAWC. We will then make sensitivity studies, *i.e.,* calculate and analyze several (Pacific/NAWC) twin solutions that differ from each other by their forcing functions or model configurations. This will help us identify and characterize the key mechanisms involved in down-scaling and up-scaling processes.

WORK COMPLETED

Progress made during the past years covers different aspects of the project:

We continued our effort to improve downscaling techniques and the boundary conditions treatment in ROMS. Using more accurate interpolation procedures we showed a significant reduction of rim currents along the boundaries of regional configurations (Mason et al., 2008). This technique is now routinely applied to downscale different OGCMs or basin-scale solutions : SODA-POP reanalysis (Carton and Giese, 2008), CCSM-POP (Large and Danabasoglu, 2006), NCEP-GODAS reanalysis (NOAA/OAR/ESRL PSD, http://www.cdc.noaa.gov/) and UCLA ROMS-Pacific.

Evaluation of the skill of those solutions in the downscaling in our regional configurations is systematically done, especially in the context of strong ENSO events. We observed that regional solutions are significantly improved when information at the open boundaries is updated on a time-scale of a few days (rather than monthly). This is due to the fact that ENSO signals have an equatorial origin and a significant part of the equatorial activity is contained in an intra-seasonal frequency range. We keep improving our home-made ROMS Pacific solutions at 50km and 25km resolutions, and in addition we have been recently developing a 12km resolution configuration.

A large part of our activity during the last years has consisted of a careful analysis of our companion interannual solutions (large domains including the equatorial region at horizontal resolution $\approx$ 8km) obtained for the NAWC and the South American West Coast (SAWC) over the period 1992-2000 (Colas et al., 2008; Kurian et al., 2008a).

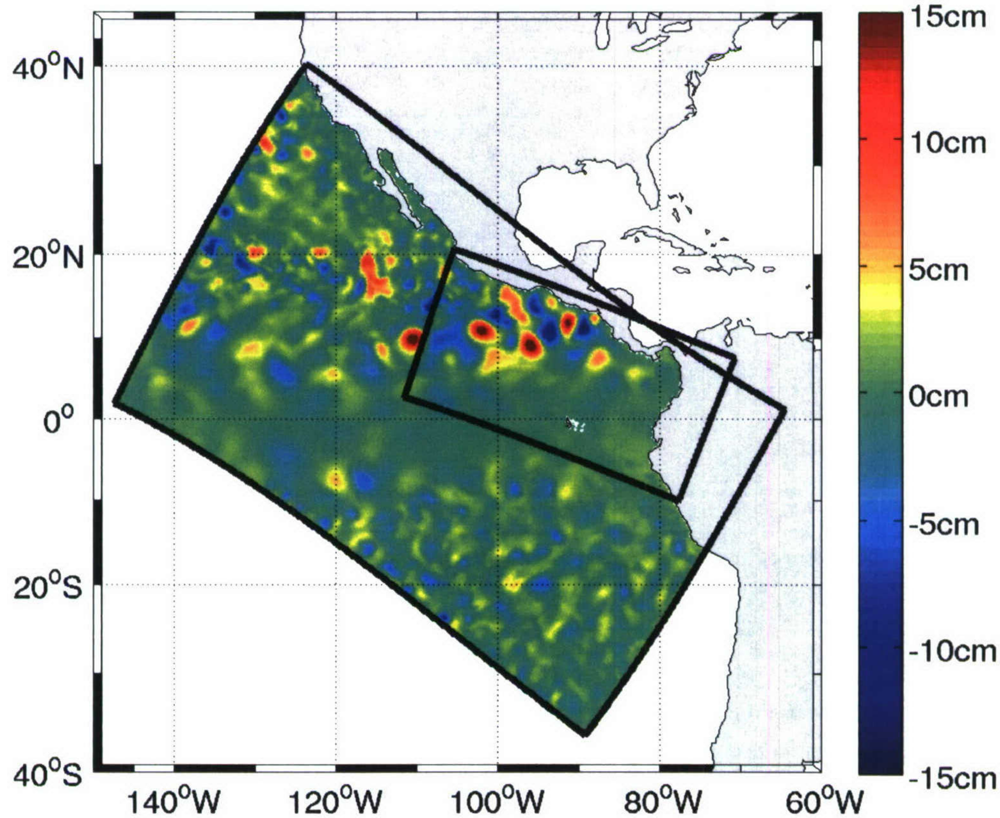

Figure 1. Sea Surface Height snapshot from the Wind Gaps climatological solution

[Sea Surface Height [cm] snapshot from ROMS Central America climatological solution. Black lines indicate domains boundaries (20 km and 7 km horizontal resolution). Large anticyclonic eddies are clearly seen generated off Central America and propagate westward.]

Building on our recent developments and experience, downscaling studies have also been undertaken in other regions of the eastern Pacific : the Gulf of Alaska and Central America. Analysis of those solutions are currently underway. The regional configuration of the Gulf of Alaska includes three different levels of embedded grids at 10 km, 3.3 km and 1.2 km horizontal resolutions. In this region the nearshore dynamics is in the complex local river-tide-current interactions, and the mesoscale activity is subject to an important interannual variability (Murray et al., 2001). Our quasi-equilibrium solutions for this configuration, forced either by SODA-POP or ROMS-Pacific at the boundaries, present a satisfactory seasonal cycle and level of mesoscale activity. Our regional configuration off Central America encompasses the "wind gaps" region (Tehuantepec, Papagayo and Panama) and the equatorial region (i.e., to ensure an efficient downscaling of equatorial signals). The configuration consists of two levels of embedded grids (20km and 7km, Fig. 1). Large coherent anticyclonic eddies are known to be generated in the wind gaps area and propagate westward. The number and size of these eddies have a clear interannual variability (Palacios and Bograd 2005), related partly to the interannual variability of the equatorial signals. For these reasons this region is a really interesting case of cross-scale coupling. Preliminary analysis shows that our solutions adequately capture the mean circulation, seasonal cycle and eddy activity (Fig.1) in the gaps region.

With the objective of understanding the modulation of the mesoscale activity by local seasonal forcing (and remote basin-scale signals), we have continued our effort to significantly improve our U.S. West Coast quasi-equilibrium solutions (Capet et al., 2008a). In the meantime we have developed a quite complete set of diagnostics to study the mesoscale processes. A special focus has been on the eddy contribution to the heat balance in coastal upwelling regions (for NAWC and SAWC in companion experiments at 5km horizontal resolution) and its possible upscaling effect. This analysis has been carried out for our quasi-equilibrium solutions (Capet et al. 2008b, Capet et al. 2008c).

Mesoscale and submesoscale eddies play a critical role in the variability of eastern Pacific, for example through offshore transport of water properties from coastal region. A better understanding of their properties, as well as variability, is central to the studies of this region. We have addressed this potential requirement by developing an automated eddy tracking and statistics tool (Kurian et al., 2008b), based on the Okubo-Weiss/Q parameter method described by Isern-Fontanet et al., (2003) and Chelton et al., (2007), for application in ROMS solutions. Extensive testing has been carried out on climatological solutions from the USWC regional configuration, and we found it to provide accurate results. The present implimentation includes 1) various tuning parameters to suit different model configurations, 2) eddy feature tests, 3) estimation of eddy properties such as center, radius, speed and track, and 4) the ability to extract model fields (and diagnosed fields such as spiciness) in the eddy-interior region. ROMS model output can be readily used with the tool for tracking eddies at surface or subsurface depths/iso-surfaces.

Efforts to address the variability of the USWC from a coupled modeling perspective has also been undertaken, using ROMS and WRF. We have designed two levels of embedded grids with horizontal resolutions of 5 and 1.5 km, and 18 and 6 km for ROMS and WRF respectively. The present strategy is to do offline coupling, and the Level-1 coupling has been tested successfully. In the Level 1 coupling, atmospheric fields from daily NARR (North American Regional Reanalysis, Mesinger et al., 2006) fields with a 32 km resolution are used to force the ROMS 5 km configuration, and the SST from this solution (together with NARR at the boundaries) has been used for forcing the 18 km WRF configuration. In the next level above, the WRF solution will be used to force ROMS Level-2 grid. Initial analysis suggested that high frequency wind forcing induces inertial oscillations in ROMS solution and care should be exercised to avoid aliasing effects. Because these oscillations are not of direct interest, for the present work we are developing effective methods to remove them.

RESULTS

A careful analysis of the 1997-98 El Nino has been carried out for the SAWC solution (Colas et al., 2008) and the NAWC solution (Kurian et al., 2007a). Emphasis was first put on the analysis of the

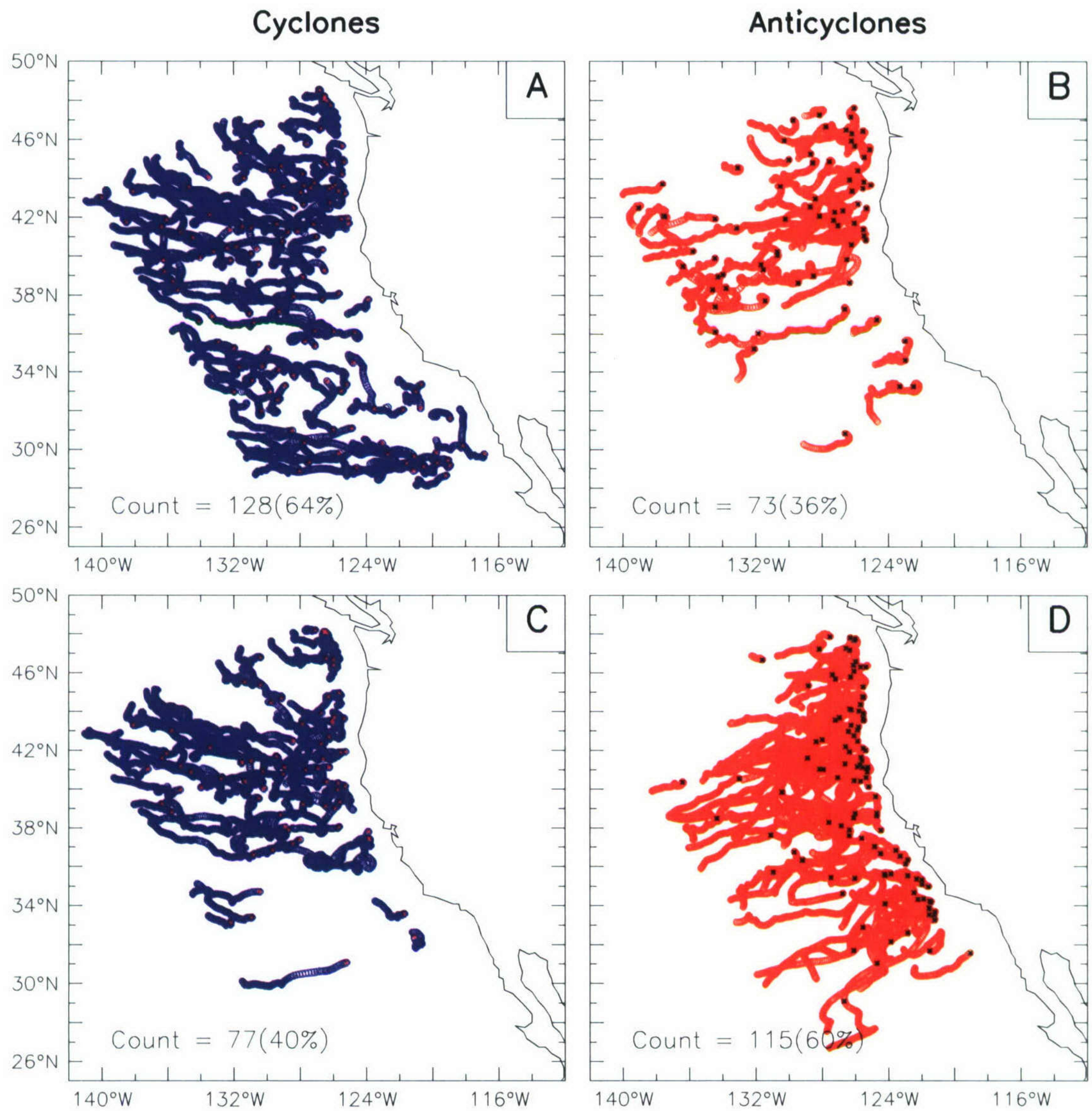

Figure 2. Eddy tracking results from USWC climatological solution

[Tracks of eddies from 9 years of USWC climatological runs, for surface (A & B) and sigma theta 26.5 surface (C & D). The pink and black markings show the initial position of eddy. Relative distribution of the eddy type is given at the bottom of each panel. Only those eddies with a minimum radius of 15 km and life time of 90 days are considered.]

SAWC region due to its direct connection with the equatorial region; this makes it a perfect testbed for Pacific signal downscaling. A model/data comparison of SLA (using tide gauges and altimeter data) for both solutions has shown that the regional model correctly captures the ENSO signals. The phase and amplitude of poleward coastal waves associated with El Nino are in agreement with the observations. Off Peru the intensity of the upwelling appears to be determined by an interplay between alongshore poleward advection, related to coastal-trapped waves, and wind intensity, but it is also determined by the cross-shore geostrophic flow and distribution of the water masses on a scale of 1000 km or more off Peru. Our solution shows that the delay of upwelling recovery until fall 1998 is partly caused by the persisent advection of offshore stratified water of equatorial origin toward the coast.

To better understand the role of the mesoscale eddies in eastern-boundary upwelling regions (also their modulation and their upscaling effect) we developed a detailed analysis of the heat balance in the NAWC and SAWC (Capet et al., 2008b, Capet et al., 2008c). For this study we developed a very similar configuration for USWC and SAWC at 5km resolution. Simultaneously, we have significantly improved our USWC quasi-equilibrium solution (forced with a SODA climatology at the open boundaries and a QSCAT wind climatology (Capet et al., 2008a). Compared with available observations, the solution presents very satisfactory seasonnal cycle, mean circulation patterns and level of mesoscale activity. The model EKE has the same level as the EKE estimated from altimetry (not shown), and their spatial distributions are very similar (with a maximum offshore and minimum nearshore off Central California).

In eastern boundary regions, where the mean circulation is generally weak, eddy fluxes can potentially influence the dynamical balances. Using these quasi-equilibrium solutions, we have examined the upper-oceanic heat balance because of its importance in the coupled atmosphere-ocean system. In those regions the heat balance is principally between the ocean-atmosphere heat flux and the advection terms (decomposed in mean and eddy contributions). In the California region, nearshore, standing eddies play an important role in shaping alternating strips of warming and cooling with magnitude over 50 W.m-2. Nearshore the eddy term produces a warming to balance the cooling by mean advection/upwelling. Further offshore, eddy flux modulates the heat budget with clear signs of cooling over extended regions having a temperature maximum located a few hundred kilometers offshore (Northern California-Oregon, Southern California Bight and off southern Peru). In these regions we find an eddy cooling equivalent to -30 W.m-2 , which indicates a locally significant effect of the eddy fluxes (hence an expected upscaling effect).

In addition to confirm some of the known features, new eddy tracking results from the 5 km USWC solution (which has shown very high eddy activity and a realistic EKE distribution, Capet et al., 2008a) has also given new insight into eddy properties and distribution over U.S. West Coast. Cyclone-anticyclone distribution shows asymmetry at surface and subsurface depths; with more cyclones at the surface and more anticylones at the subsurface (Fig.2). While cyclones show a tendency for northwestward translation, anticyclones preferably move southwestward. The coastal region north of Pt. Arena ($\sim 39°$N) is a highly active eddy generation region (Fig.2). The region to the south of it shows a striking difference with respect to eddy type and depth; sparse formation of anticyclones at the surface and cyclones at the subsurface. The subsurface anticyclones generally form very close to the coast, suggesting the California Undercurrent as their source. Their intensity, offshore translation and life time clearly indicates that a good share of offshore transport of water properties could be regulated by them. Regional differences in eddy formation and distribution along the USWC have strong implications for the general variability and biological aspects of this region. Efforts to study the formation, variability and climate impact of eddies along USWC are underway.

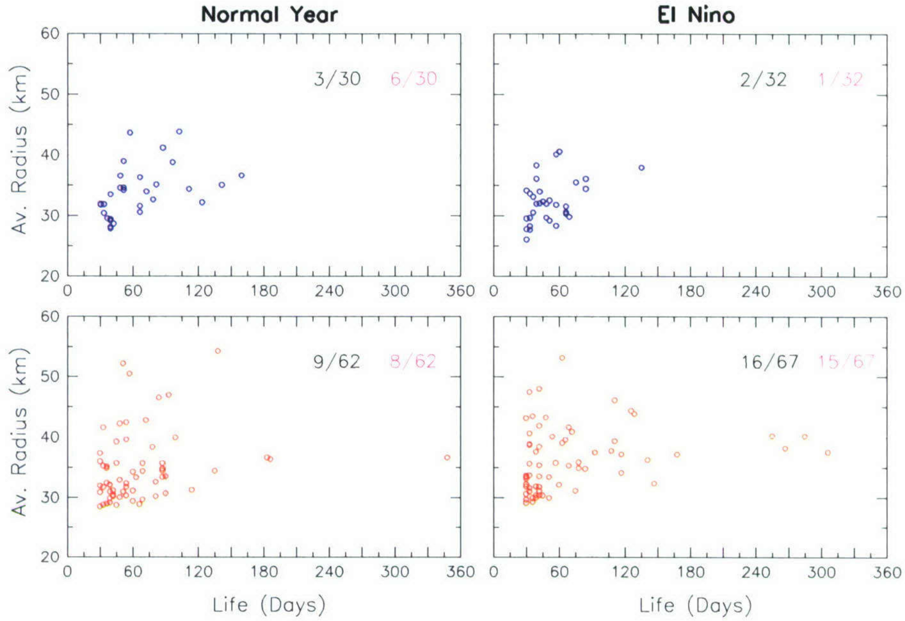

Figure 3. Eddy properties during normal and El Niño years

[Mean radius (km) and life period (days) of cyclones (upper panel) and anticyclones (lower panel) on a 25.8 sigma theta surface, from 8 km NAWC interannual simulation, during normal (left panel, November/1995-October/1996) and El Niño (right panel, November/1997-October/1998) years. The numbers inside the plot shows bigger (radius > 40 km, black) and long-lived (> 90 days, pink) cyclones or anticyclones, with respect to the total number of cyclones or anticyclones. Only those eddies with a minimum radius of 25 km and life period of 30 days formed over USWC region are considered. Please note that the number of long-lived (> 90 days) cyclones varies significantly during normal years.]

Both in the NAWC and SAWC solutions, mesoscale activity appears to be modulated at interannual scales with conspicuous mesoscale eddy formation along the coast associated with El Niño pulses. Eddy tracking algorithm used in the interannual NACW solution for 1994-1999 demonstrate this. In the USWC region (140-110°W, 25-50°N), the eddy properties change during El Niño though there is only a slight change in the total number of eddies formed. A typical example is the increase in the number of short-lived (30-90 days) and bigger (radius > 40 km) anticyclones. More long-lived (> 90 days) and smaller (radius < 40 km) anticyclones form during El Niño (Fig.3) and in previous year. Cyclones do not exhibit any such systematic differences in this model solution. During El Niño years, the coastal waves efficiently transport spicy equatorial water poleward along the coast. This spicy water is transported offshore by anticyclones. One example, along with the life cycle identified from eddy tracking tool, is given in Fig.4. Efforts to address the impact of such climate signals on mesoscale and submesoscale activity, at high-resolution USWC configuration, have been undertaken.

IMPACT/APPLICATIONS

This research will significantly contribute to the understanding of how large scale variability affects coastal properties that are difficult to measure (retention, dispersion and more generally properties intimately linked to oceanic turbulence) but are, nonetheless, essential oceanic variables (for operational, biogeochemical, as well as environmental reasons). Simulations including biogeochemistry are currently

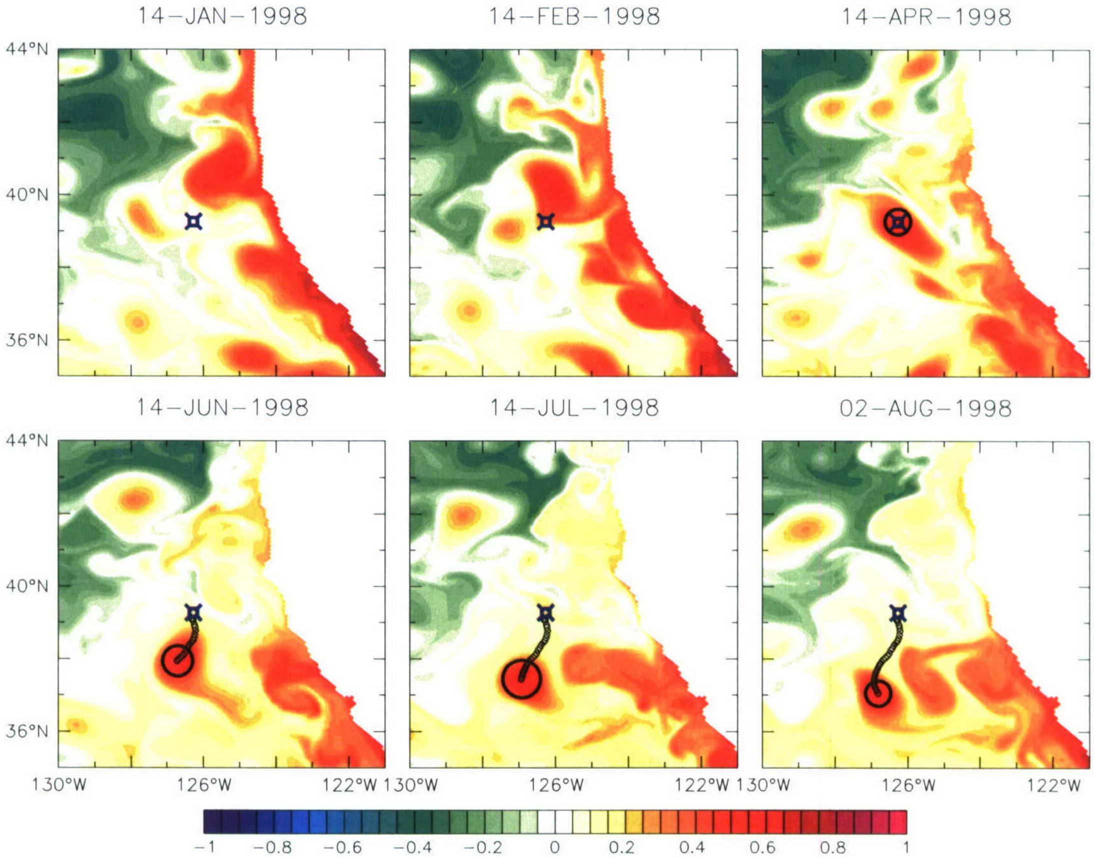

Figure 4. Track of an anticyclonic eddy formed during El Niño

[Track of an anticyclonic eddy formed during El Niño and spiciness on 25.8 sigma theta surface. The mean radius of the eddy is 46 km and had a life period about 110 days. The blue symbol shows the inital position of eddy, big circle shows the circle fitted to eddy, and the small black circles shows the eddy track, according to the eddy tracking tool.]

being computed for the 1990s decade, in collaboration with N. Gruber (ETH and UCLA).

TRANSITIONS & RELATED PROJECTS

This project is being done within a broader context both of coastal circulation modeling and forecasting using ROMS (*e.g.,* ONR's AOSN project in Monterey Bay, the Southern California (http://www.sccoos.org/), Central California (http://www.cencoos.org/), and Prince Williams Sound Coastal Oceanic Observing Systems (http://www.aoos.org). All these efforts will directly contribute to improved understanding of down-scaling mechanisms in the NAWC region. The Southern America part of this research is expected to be pursued in the framework of the VOCALS program (http://www.eol.ucar.edu/projects/vocals/).

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